What Can we Learn about Θ Baryon from Unified Picture for Hadron Spectra?

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Abstract

An analysis of the recent results from several experimental groups reported observation of a new Θ baryon has been presented from a view point of the unified picture for hadron spectra developed early [12]. It is shown that, in fact, two different Θ baryons have been discovered. We have also established that both Θ baryons are excellently incorporated in the unified picture for hadron spectra. It is argued that the presented experimental material revealed an existence of the positive srangeness Θ partners for the observed Λ and Σ states with negative strangeness as we predicted.

1 Introduction

The first experimental observation of a new, manifestly exotic baryon (B=1, S=1, originally called the Z^+ but now denoted as the Θ^+) has been reported by LEPS Collaboration [1]. The experiment was carried out at the Laser-Electron Photon facility at SPring-8 in Japan. A sharp baryon resonance peak for the strangeness quantum number S=+1 was found at 1.54 ± 0.01 GeV in the K^- missing mass spectrum of the $\gamma n \to K^+K^-n$ reaction on ^{12}C. The width of the resonance was estimated to be smaller than 25 MeV and Gaussian significance of the peak was 4.6 σ. Soon after the confirmation of this observation was received by several experimental groups [2, 3, 4, 5, 6, 7] from different experiments where sharp peaks were observed in the nK^+ and pK_S^0 invariant mass spectra at the mass near 1540 MeV. As a rule, in all experiments a width was limited by the experimental resolution.

DIANA Collaboration [2] reported results from analysis of bubble-chamber data for the charge-exchange reaction $K^+Xe \to K^0pXe'$ where the spectrum of K^0p effective mass shows a resonant enhancement with M = 1.539 ± 0.002 GeV and $\Gamma \le 9$ MeV. The statistical significance of the enhancement is near 4.4 σ.

A narrow peak in the K^+n invariant mass spectrum that can be attributed to exotic baryon with strangeness S=+1 was seen by CLAS Collaboration [3] in exclusive measurement of the reaction $\gamma d \to K^+K^-pn$. This peak is at 1.542 ± 0.005 GeV with a measured width of 0.021 GeV, which is largely determined by experimental mass resolution, and has a statistical significance 5.3 ±0.5 σ.

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The positive-strangeness baryon resonance Θ^+ was observed in photoproduction of the $nK^+K^0_s$ final state with the SAPHIR detector at the Bonn Electron Stretcher Accelerator ELSA [4]. It was seen as a peak in the nK^+ invariant mass distribution with a 4.8σ confidence level at the mass M_{Θ^+}=1540±4±2 MeV with an upper limit of the width $\Gamma_{\Theta^+} \leq 25$ MeV at 90% c.l.

ITEP group [5] reported an evidence for formation of a narrow $K^0_S p$ resonance with the mass estimated as 1533±5 MeV in neutrino and antineutrino collisions with nuclei. The observed width is less than 20 MeV being entirely due to experimental resolution, and statistical significance of the signal is near 6.7 standard deviations. It is supposed that this resonance arises from neutrino production of the Θ^+ pentaquark baryon. The performed analysis was based on the data obtained in past neutrino experiments with big bubble chambers: WA21, WA25, WA59, E180, and E632.

A new, more comprehensive study of the Θ^+ production on a proton target has been done by CLAS Collaboration [6]. Two reactions, $\gamma p \to \pi^+ K^+ K^- n$ and $\gamma p \to K^+ K^- p$, were studied at Jefferson Lab using a tagged photon beams with energy range of 3.5-4.7 GeV. A narrow baryon state with strangeness S=+1 and mass M=1555±10 MeV was observed in the nK^+ invariant mass spectrum. The peak's width is close to the experimental mass resolution (FWHM =26 MeV) of the CLAS detector, and its statistical significance is 7.8±1.0 σ. Besides, the pK^+ invariant mass distribution was analyzed in the reaction $\gamma p \to K^- K^+ p$ too, and no resonance structure was found there.

HERMES Collaboration [7] presented the results of a search for the Θ^+ in quasi-real photoproduction on a deuterium target through the decay channel $pK^0_S \to p\pi^+\pi^-$. A peak was observed in the pK^0_S invariant mass spectrum at 1528 ± 2.6(stat) ± 2.1(syst) MeV. Depending on the background model, the naive statistical significance of the peak is 4-6 standard deviations and its width may be somewhat larger than the experimental resolution of σ=4.3-6.2 MeV. In addition, no signal for the Θ^{++} baryon was observed in the pK^+ invariant distribution.

The most recent experimental evidence for the Θ^+ came from ZEUS Collaboration [8] and SVD Collaboration [9]. ZEUS Collaboration presented preliminary results of an evidence for exotic baryon decaying to K^0_S-(anti)proton: a signal at 1527±2(stat) MeV with a Gaussian width of 10 ± 2 MeV and statistical significance 4-5 σ (from Gaussian fit) has been observed for both K^0-proton and K^0-antiproton channels. SVD Collaboration also reported an experimental observation a resonant structure with M=1526 $\pm$ 3(stat) $\pm$ 3(syst) MeV and $\Gamma \leq 24$ MeV in the pK^0_S invariant mass spectrum in the reaction $pA \to pK^0_S + X$.

It should be emphasized that the search for baryon resonances with the strangeness S=+1, that cannot be built by three quarks, has a long and interesting history, and first experimental observation of a new, manifestly exotic baryon reported by LEPS Collaboration [1] was motivated in part by theoretical studies [10] where baryon's anti-decuplet has been constructed in the framework of chiral soliton model exploiting the old and deep idea of Skyrme [11]. Taking the mass of $P_{11}(1710)$ nucleon resonance as input identifying that resonance with the member of the constructed anti-decuplet, it was predicted a mass of ~1530 MeV and a total width of less than 15 MeV for the Z^+ (spin 1/2, isospin 0 and strangeness +1) baryon and pointed out that this region of the masses has avoided thorough searches before. In particular, the S=+1 baryon resonances with a relatively low mass of about 1530 MeV have not been searched for in the KN scattering in the past, probably, because momenta of kaons were too high. Nevertheless, some claims for observ-

ing baryon states decaying into K^+n and K^0p have been made in the past (see e.g. old Particle Data Group Booklets in the middle of 70th) but they were all with substantially higher mass and larger width than the prediction in [10].

Since the simplest quark assignment consistent with the quantum numbers of the Θ^+ is ($uudd\bar{s}$), this baryon is often called pentaquark. So, the first problem arises how to describe pentaquark states in QCD. This problem is extremely complicated even though on a pure empirical base e.g. what quark configuration is favorable for the Θ^+: is it diquark-triquark pentaquark state or this is the state of antiquark and two diquarks or something else. It is well known that a description of new, recently discovered charmonium meson states with unexpectedly low masses and narrow total decay widths is extremely problematic in the framework of phenomenology based on conventional quark potential models. Now, it appears on a more high level with pentaquark states. Here, a similar story repeats itself: the discovery of exotic baryon with low mass and narrow width brings new, yet more serious problems for that phenomenology. Concerning pure theory, up to now our theoretical understanding of (especially low-energy) QCD is far from what is desired. We don't know in quantum field theory how to construct even the states for protons and pions though from fundamental quark and gluon degrees of freedom in QCD, it appears to be very complicated and unresolved problem so far. The best currently performed lattice computations in QCD cannot help us to make calculations accurately at low energy too. Nevertheless, there is a hope that powerful computers will allow to overcome many significant technical problems in the future.

In Ref. [12], where some of our previous studies were partially summarized, it has been claimed that existence of the extra dimensions in the spirit of Kaluza and Klein together with some novel dynamical ideas may provide new conceptual issues for the global solution of the spectral problem in hadron physics to create a unified picture for hadron spectra. The question arises: what place in the unified picture for hadron spectra the Θ baryon takes up? This paper presents the answer to that question.

2   Unified picture for hadron spectra: Understanding the Θ baryon in comparison with the experiments

Recently a new, very simple and at the same time quite general physical law concerning the structure of hadron spectra has been found; see [12] and references therein. The developed theoretical conception allowed to construct the global solution of the spectral problem in hadron spectroscopy and provided quite new scheme of systematics for hadron states. Our approach to hadron spectroscopy has been verified with a large amount of experimental data on meson's states and received an excellent agreement. What is remarkable that all new meson states experimentally discovered last year have been observed just at the masses predicted in our approach, and those states appeared to be narrow as predicted too. The main advantage of our developed theoretical conception is that all calculated numbers for masses and widths do not depend on a special dynamical model but follow from fundamental hypothesis on existence of the extra dimensions with a compact internal extra space. One very important fact has been established now in a reliable way: the size of the internal compact extra space determines the global characteristics of the hadron spectra while the masses of the constituents are the fundamental parameters of the compound systems being the elements of the global structure. Here we apply our approach to analyse

the hadron system under consideration i.e. kaon-nucleon system.

First of all, according to the general law, the Kaluza-Klein tower of KK-excitations for the kaon-nucleon system has been built by the formula

$$M_n^{NK} = \sqrt{m_N^2 + \frac{n^2}{R^2}} + \sqrt{m_K^2 + \frac{n^2}{R^2}}, \quad (n = 1, 2, 3, ...),\qquad(1)$$

where $(N = p, n)$ and $(K = K^0, K^+, K^-)$, R is the fundamental scale established before from analysis of nucleon-nucleon dynamics at low energies; see [12] and references therein for the details. The such built Kaluza-Klein tower is shown in Table 1. Some experimental information known from RPP Booklet has been presented in this Table as well.

For completeness we have also calculated the Kaluza-Klein tower of KK-excitations for the $\Lambda\pi$ system by similar formula like (1). That Kaluza-Klein tower is shown in Table 2 together with experimental information extracted from the same RPP source. We very hope that both Tables 1 and 2 might serve as a guide for the experimenters in particle physics.

Now we would like to compare the theoretically calculated spectra with experimental material presented in above mentioned papers; see Introduction. So then, let's see one after another.

2.1   DIANA Collaboration experiment

DIANA Collaboration investigated low-energy K^+Xe collisions by the bubble chamber filled with liquid Xenon which has been exposed to a separated K^+ beam with momentum of 850 MeV/c from the ITEP proton synchrotron. The spectrum of K^0p effective mass was analyzed in the charge-exchange reaction $K^+n \to K^0p$ where the neutron was bound in a Xenon nucleus. The events of this reaction were fully measured and reconstructed in space using specially designed stereo-projectors; the details on the experimental procedure can be found in original paper [2].

Effective mass of the K^0p system formed in the charge-exchange reaction is plotted in Fig. 1a for all measured events where an enhancement is clear seen at the mass $M \simeq 1540$ MeV/c^2. To estimate the level of background, the effective mass spectrum was fitted to a linear combination of two regular distributions: one distribution was obtained by simulation that took into account many real conditions of the experiment, and a distribution which was obtained by the method of random stars. The result of the fit is depicted by the dashed line in Fig. 1a. After that, additional topological selections have been applied: see [2] for details. Of the 1112 measured events, nearly a half (541 events) survived the additional selections. In the K^0p mass spectrum for these events, that is shown in Fig. 1b, the enhancement near 1540 MeV/c^2 became more prominent.

In summary it has been concluded that a baryon resonance with mass $M = 1539 \pm 2$ MeV and width $\Gamma \leq 9$ MeV has been observed in the K^0p effective-mass spectrum. The statistical significance of the signal was estimated as 4.4σ. It is suggested that the observed resonance is a strong indication for formation of the exotic pentaquark Z^+ baryon, but the work is still in progress.

Vertical, spectral lines have been plotted in Figs. 1a and 1b as well to compare the theoretically calculated spectrum of KK excitations in the K^0p system with the picture observed at the experiment. Even though we found a strong correlation of the spectral

lines with the peaks on the histograms the reported resonance peak appeared approximately in the middle between two spectral lines corresponding to $M_6^{pK^0}(1527)$-storey and $M_7^{pK^0}(1558)$-storey in KK tower for pK^0 system; see Table 1. Let's assume that further, thorough analysis would clarify a matter of dispute.

2.2 CLAS Collaboration γd experiment

CLAS Collaboration [3] has performed an exclusive measurement on deuterium for the reaction $\gamma d \rightarrow K^+K^-p(n)$ where the final state neutron was reconstructed from the missing momentum and energy. The data have been obtained at the Thomas Jefferson National Accelerator Facility with the CLAS detector and the photon tagging system: photon beams were produced by 2.474 and 3.115 GeV electrons incident on a bremsstrahlung radiator, the maximum tagged photon energy was 95% of the electron beam energy, the photons struck a liquid-deuterium target; see [3] and references therein for details. The details on the experimental procedure as well as a discussion of the explicit cuts which have been made to remove the main background sources from the final event sample in order to enhance the signal relative to background can be found in original paper [3] too.

Final result is presented as nK^+ invariant mass spectrum which is shown in Fig. 2. A fit (solid line) to the peak and a Gaussian plus constant term fit to the background (dashed line) are also depicted in this Figure. The peak is at 1.542 ± 0.005 GeV with a width (FWHM) of 0.021 GeV. The width is consistent with the instrumental resolution. The uncertainty of 0.005 GeV in the mass is due to calibration uncertainties of the photon tagging spectrometer, the electron beam energy, and the momentum reconstruction in CLAS. The statistical significance of the peak is 5.2 ± 0.6 σ. The spectrum of events removed by the $\Lambda(1520)$ cut is shown in Fig. 2 by the dashed-dotted histogram, and does not appear to be associated with the peak at 1.542 GeV.

The invariant mass spectrum of pK^+ system was also examined by CLAS Collaboration using the same event selection as in the case of nK^+ system. The statistics were limited, but there was no clear peak in the signal region. It was noted that the CLAS acceptance for the pK^+ system is not the same as for the nK^+ system, so the two spectra are not directly comparable. The absence of peak in $M(pK^+)$ spectrum suggests that Θ^+ is probably an isosinglet, though there is no a firm conclusion based on the current data.

We have plotted in Fig. 2 the spectral lines corresponding to KK excitations in the nK^+ system taken from Table 1. Here it is also found a strong correlation of the spectral lines with the peaks on the histogram. The reported resonance peak appeared between two spectral lines corresponding to $M_6^{nK^+}(1525)$-storey and $M_7^{nK^+}(1556)$-storey in KK tower for nK^+ system though a little bit closed in second spectral line of $M_7^{nK^+}(1556)$.

2.3 SAPHIR Collaboration experiment

SAPHIR Collaboration [4] presented evidence for the Θ^+ in photoproduction of the $nK^+K_s^0$ final state off protons. Actually, the reaction $\gamma p \rightarrow nK_s^0K^+$ with the decay $K_s^0 \rightarrow \pi^+\pi^-$ was measured with the SAPHIR detector at ELSA. The ELSA electron beam produced photons via bremsstrahlung in a copper foil radiator. The tagged photon energies were from 31 % to 94 % of the incident electron energy which was 2.8 GeV for the data presented in this experiment. The photon beam passed through a liquid hydrogen target. Non–interacting photons were detected in a photon counter. The coincidences

of tagger and photon counter determined the photon flux. Additional, needed details concerning the experimental procedure can be found in original paper [4].

The observation of the Θ^+ in the reaction chain

$$\gamma p \to \Theta^+ K_s^0, \qquad \Theta^+ \to nK^+, \qquad K_s^0 \to \pi^+ \pi^- \qquad (2)$$

has been presented by Fig. 3 showing the nK^+ invariant mass distribution after cuts; original paper [4] contains a comprehensive discussion of all cuts which have been made to arrive at this Figure. As is seen from Fig. 3 there is a clear peak at $\sim 1540\,\text{MeV}$. The statistical significance of the peak is 5.2σ.

The photoproduction of the pK^+K^- final state has been studied by SAPHIR Collaboration as well to search for the doubly charged Θ^{++} in the reaction chain

$$\gamma p \to \Theta^{++} K^-, \qquad \Theta^{++} \to pK^+. \qquad (3)$$

Fig. 4 shows the resulting pK^+ invariant mass spectrum. It should be emphasized that the data are consistent with a small structure in the pK^+ invariant mass distribution. However, since the SAPHIR acceptance was considerably larger for the fully constrained pK^+K^- events they expected a peak with more than 5000 Θ^{++}, far above the observed level. The absence of a signal in the pK^+ invariant mass distribution at the expected strength resulted in conclusion that the Θ^+ must be isoscalar.

As before we have plotted in Figs. 3 and 4 the spectral lines corresponding to KK excitations in the nK^+ and pK^+ systems taken from Table 1. Again we found a strong correlation of the spectral lines with the peaks on the histograms. The reported resonance peak of Θ^+ in Fig.3 appears just in the middle between two spectral lines corresponding to $M_6^{nK^+}(1525)$-storey and $M_7^{nK^+}(1556)$-storey in KK tower for nK^+ system (see Table 1), and this peak is broad enough. However, we would like to point out a remarkable fact that the spectral line $M_7^{pK^+}(1555)$ in Fig.4 exactly coincided with the experimentally observed structure in the pK^+ invariant mass distribution. In our opinion further, scrupulous experimental studies of kaon-nucleon system are very desirable, no doubt they would welcome.

2.4   NEUTRINO interactions

ITEP group reported a search for formation of the Θ^+ baryon in neutrino and antineutrino collisions with protons, deuterons, and Neon nuclei [5]. The data collected by several neutrino experiments with big bubble chambers – BEBC at CERN and the 15-foot chamber at Fermilab – have been analyzed. Compiled database included about 120 000 ν_μ and $\bar{\nu}_\mu$ induced charged-current events, and covered the bulk of neutrino data collected with BEBC (WA21, WA25, and WA59) and a significant fraction of data collected with the 15-foot bubble chamber at Fermilab (E180 and E632). Neutral-current interactions were not systematically included in the database, and therefore the analysis was restricted to charged-current events only. It has been stressed that neutrino data from big bubble chambers are still unrivaled in quality and completeness of physics information. Further details on the neutrino experiments can be found in original paper [5] and references therein.

Figure 5 shows the $K_S^0 p$ invariant mass distribution for the Neon and Deuterium data combined (top panel). In the bottom panel the same $K_S^0 p$ distribution with bins shifted

by 5 MeV has been plotted. A fit of the bottom histogram yielded $M = 1533 \pm 5$ MeV and $\sigma = 8.4 \pm 2.0$ MeV for the position and r.m.s. width of the resonance. The statistical significance of the peak appeared to be near 6.7 standard deviations.

We have plotted in Fig. 5 (top panel) the spectral lines corresponding to KK excitations in the pK^0 system taken from Table 1 and found a striking picture: all spectral lines without any exception coincided with the peaks on the histogram. The reported resonance peak of Θ^+ just corresponds to the spectral line $M_6^{pK^0}(1527)$ in KK tower for pK^0 system (see Table 1). Really, analyzing the excellent neutrino data resulted in excellent agreement with the theory.

2.5 CLAS Collaboration γp experiment

Recently a more comprehensive study of the Θ^+ production on a proton target which includes data from three distinct runs under different experimental conditions in CLAS has been reported by CLAS Collaboration [6]. Two reactions, $\gamma p \to \pi^+ K^+ K^- n$ and $\gamma p \to K^+ K^- p$, have been analyzed in the three runs having identical geometrical acceptance and trigger requirement but with a slightly different tagged photon beams in the energy range of 3.2–3.95 GeV, 3–5.25 GeV, and 4.8–5.47 GeV, respectively (details described in [6]). The combined analysis of these three runs offered access to a wider range of acceptance and energies. The final nK^+ invariant mass spectrum calculated from missing mass in the reaction $\gamma p \to \pi^+ K^- X$, combining data from all three data runs, is shown in Fig. 6. The authors concluded that no obvious structure is seen in this spectrum.

Figure 7 shows the resulting nK^+ mass spectrum prepared by applying a several explicit angular cuts. As is seen the Θ^+ peak was clearly observed in that Figure. The nK^+ effective mass distribution shown in Fig. 7 was fitted by the sum of a Gaussian function and a background function obtained from the simulation. The fit parameters are: $N_{\Theta^+} = 41 \pm 10$, $M = 1555 \pm 1$ MeV, and $\Gamma = 26 \pm 7$ MeV (FWHM), where the errors are statistical. The systematic mass scale uncertainty was estimated to be ± 10 MeV. It was also estimated the significance to be $7.8 \pm 1.0 \, \sigma$.

In addition, a search for a manifestly exotic baryon ($Q = 2$, $S = +1$) was performed in the reaction $\gamma p \to K^- X^{++}$, $X^{++} \to pK^+$. Using the similar procedures as in previous case, the pK^+ invariant mass distribution was built but there were no resonance structures evident in that distribution. However, a more detailed analysis will be presented in a future.

As usual, we have plotted in Figs. 6 and 7 the spectral lines corresponding to KK excitations in the nK^+ system taken from Table 1. Here, in addition to strong correlation of the spectral lines with the peaks on the histograms as in previous cases, we found out new, quite a remarkable fact: The reported resonance peak of Θ^+ just corresponds to the spectral line $M_7^{nK^+}(1556)$ in KK tower for the nK^+ system (see Table 1).

2.6 HERMES Collaboration experiment

The results of a search for the Θ^+ in quasi-real photoproduction on deuterium have been presented by HERMES Collaboration [7]. The data were obtained by the HERMES experiment with the 27.6 GeV positron beam of the HERA storage ring at DESY. The analysis searched for inclusive photoproduction of the Θ^+ followed by the decay chain $\Theta^+ \to pK_S^0 \to p\pi^+\pi^-$. Events selected contained at least three tracks: two oppositely

charged pions in coincidence with one proton. The event selection included constraints on the event topology to maximize the yield of the K_S^0 peak in the $M_{\pi^+\pi^-}$ spectrum while minimizing its background. However, no constraints were optimized to increase the significance of the signal visible in the final $M_{p\pi^+\pi^-}$ spectrum, as such optimization would have produced a spectrum to which standard statistical tests do not apply. To search for the Θ^+, events were selected with a $M_{\pi^+\pi^-}$ invariant mass within $\pm 2\,\sigma$ about the centroid of the K_S^0 peak. More details on the experimental procedure described in original paper [7] where the interested reader referred to. The resulting spectrum of the invariant mass of the $p\pi^+\pi^-$ system is displayed in Fig. 8. As is seen a narrow peak is observed, and this peak is identified with the Θ^+.

Figure 9 shows the spectra of invariant mass M_{pK^-} (top) and M_{pK^+} (bottom). The event selection for the spectra in this figure was the same as for the pK_S^0 analysis, except the reconstructed K_S^0 track was replaced by that of the observed charged kaon. The $\Lambda(1520)$ mass peak fitted with a Gaussian is shown in the M_{pK^-} spectrum of Fig. 9 (details of the fit can be found in the original paper). A clear peak is seen for the $\Lambda(1520)$ in the M_{pK^-} invariant mass distribution. However, no peak structure is seen for the hypothetical Θ^{++} in the M_{pK^+} invariant mass distribution near $1.53\,\mathrm{GeV}$.

Following our general strategy, as before, we have plotted in Figs. 8 and 9 the spectral lines corresponding to KK excitations in the pK^0 system (Fig. 8) and $pK^\pm$ system (Fig. 9) taken from Table 1. No doubt, this is quite a remarkable fact that the reported resonance peak of Θ^+ exactly coincided with the spectral line $M_6^{pK^0}(1527)$ in KK tower for the pK^0 system, and $\Lambda(1520)$ peak just corresponds to the spectral line $M_6^{pK^\pm}(1523.6)$ in KK tower for the $pK^\pm$ system (see Table 1). Moreover, we observe a barely visible structures in the M_{pK^+} invariant mass distribution around the spectral lines depicted in Fig. 9. Clearly, a much more careful experimental studies with a higher statistics and resolution are utterly desired.

2.7   SVD Collaboration experiment

SVD Collaboration [9] presented the preliminary results of a search for the Θ^+ in proton-nuclei(C,Si,Pb) interactions at 70 GeV($\sqrt{s}$=11.5 GeV) IHEP accelerator (Protvino) with the SVD-2 setup in the reaction chain: $pN \to \Theta^+ X$, $\Theta^+ \to pK_s^0$, $K_s^0 \to \pi^+\pi^-$ (SVD-2 experimental setup described in the paper). The data analysis was done in the inclusive reactions with the limited multiplicity in the proton beam fragmentation region. The resulting pK_s^0 effective mass distribution before the cuts is shown in Fig. 10. The authors point out that no obvious structure in this spectrum is seen, however there is a small enhancement in the 1530 MeV mass region. After applying a special cuts (details of cuts procedure can be found in original paper) a narrow peak in the pK_s^0 effective mass distribution was seen at the mass $M = 1526 \pm 3$ MeV with a $\sigma = 10 \pm 3$ MeV. The statistical significance of this peak was estimated to be of $5.6\,\sigma$.

As it should be, we have also plotted in Fig. 10 the spectral lines corresponding to KK excitations in the pK^0 system taken from Table 1. Apart from strong correlation of the spectral lines with the peaks on the histogram in Fig. 10, here is found out too that the above mentioned "small enhancement in the 1530 MeV mass region" just corresponds to the spectral line $M_6^{pK^0}(1527)$ in KK tower for the pK^0 system (see Table 1).

2.8 ZEUS Collaboration experiment

Unfortunately, we didn't have in hand the published paper of ZEUS Collaboration. However, we can arrive at Ref. [8] by <www> where the preliminary results of an evidence for exotic baryon decaying to K_S^0-(anti)proton were presented. A signal at 1527 ± 2(stat) MeV with a Gaussian width of 10 ± 2 MeV and statistical significance 4-5 σ (from Gaussian fit) has been observed. The measured mass is in excellent agreement with the predicted state $M_6^{pK^0}(1527)$ from KK tower for the pK^0 system (see Table 1). What is remarkable here that ZEUS Collaboration observed this state for both K^0-proton and K^0-antiproton channels as we predicted too.

Recently ZEUS Collaboration papers arrived at LANL e-print archive [13, 14] where we found that a resonance search has been made in the $K_S^0 p$ and $K_S^0 \bar{p}$ invariant mass spectrum measured with the ZEUS detector at HERA using an integrated luminosity of 121 pb^{-1}, taken between 1996 and 2000. The $K_S^0 p(\bar{p})$ invariant mass spectrum has been studied in the central rapidity region of inclusive deep inelastic scattering at an ep center-of-mass energy of 300–318 GeV for a large range in the exchanged-photon virtuality, Q^2, above 1 GeV^2. The results presented there support the existence of exotic baryon decaying to K_S^0-(anti)proton, and these results constitute first evidence for the production of such a state in a kinematic region where hadron production is dominated by fragmentation. The peak position, determined from a fit to the mass distribution in the kinematic region $Q^2 \geq 20$ GeV^2, is 1521.5 ± 1.5(stat.)$^{+2.8}_{-1.7}$(syst.) MeV, and the measured Gaussian width of $\sigma = 6.1\pm1.6$(stat.)$^{+2.0}_{-1.4}$(syst.) MeV is above, but rather close to the experimental resolution of 2.0 ± 0.5 MeV. The signal is visible at high Q^2 and, for $Q^2 > 20$ GeV^2, contains 221 ± 48 events. The statistical significance, estimated from the number of events assigned to the signal by the fit, varied between 3.9σ and 4.6σ depending upon the treatment of the background. The mass of the Θ^+ baryon resonance reported now lies somewhat below the average mass of the previous preliminary results [8]. This is because some additional cuts (energy and K* cuts) were removed in the final analysis compared to the previous preliminary results, and only dE/dx cuts were saved to get a good purity for the proton sample. The ZEUS final results [13, 14] agree still with the ZEUS preliminary results [8] (without systematics) though.[2]

The result of the fit using two Gaussians is shown in Fig. 11. It was found that the second Gaussian significantly improved the fit in the low mass region. It has a mass of 1465.1 ± 2.9(stat.) MeV and a width of 15.5 ± 3.4(stat.) MeV and may correspond to the $\Sigma(1480)$. However, as pointed out, the parameters and significance of any state in this region are difficult to estimate due to the steeply falling background close to threshold. The probability of the 1522 MeV signal anywhere in the range 1500–1560 MeV arising from statistical fluctuation of the background was below 6×10^{-5}. For a more realistic case, when the starting background distribution included the 1465 MeV Gaussian the probability was found to be about a factor of ten lower.

In order to determine the natural width of the state, the Breit-Wigner function convoluted with the Gaussian was used in the fitting procedure to describe the peak near 1522 MeV. If the width of the Gaussian was fixed to the experimental resolution, the estimated intrinsic width of the signal turned out $\Gamma = 8\pm4$(stat.) MeV. The systematical error on this width was expected to be smaller than the statistical error, but due to low statistics, complicated background and the narrowness of the peak leading to unstable

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[2]I thank S. Chekanov for clarification of this point.

fits, full systematical uncertainty was difficult to estimate [14].

The invariant mass spectrum was also investigated for the $K_S^0 p$ and $K_S^0 \bar{p}$ samples separately. This result is shown as an inset in Fig. 11 for $Q^2 > 20$ GeV^2. The results for two decay channels are compatible, though the number of $K_S^0 \bar{p}$ candidates is systematically lower. The mass distributions were fitted using the same function as the combined sample and gave statistically consistent results for the peak position and width. The number of events in the $K_S^0 \bar{p}$ channel is 96 ± 34. If one considers the signal in the $K_S^0 p$ channel as the Θ^+ then the signal in the $K_S^0 \bar{p}$ channel might be identified with the Θ^-. This is quite a new, remarkable observation made by ZEUS Collaboration.

Besides, the $K^{\pm} p (K^{\pm} \bar{p})$ invariant mass spectra were investigated for a wide range of minimum Q^2 values as well, identifying proton and charged kaon candidates using dE/dx in a kinematic region similar to that used in the $K_S^0 p (\bar{p})$ analysis. For $Q^2 > 1$ GeV^2, no peak was observed near 1522 MeV in the $K^+ p$ spectrum, while a clean 10σ signal was observed in the $K^- p (K^+ \bar{p})$ channel at 1518.5 ± 0.6(stat.) MeV, corresponding to the PDG $\Lambda(1520)D_{03}$ state; see Fig. 5 in [14].

The $K^+ p$ and $K^- p$ mass spectra were especially investigated at $Q^2 > 20$ GeV^2, where the 1522 MeV peak is clearly pronounced for the $K_S^0 p (\bar{p})$ channel. Again, no sign of a peak was found in the $K^+ p$ decays; see Fig. 6 in [14].

However, we would like to emphasize, looking at the Figures 5 and 6 in [14], one cannot definitely conclude that no structures are seen in the $K^+ p$ mass spectra. Certainly, more statistics and higher mass resolution are needed to make a physically adequate statement.

We have plotted in Fig. 11 the spectral lines corresponding to KK excitations in the pK^0 system taken from Table 1. As seen in Fig. 11, the spectral lines of the $M_3^{pK^0}(1460)$, $M_4^{pK^0}(1477)$ and $M_5^{pK^0}(1500)$ from Kaluza-Klein tower for kaon-nucleon system may correspond to the observed structures in invariant mass spectra for the $K_S^0 p (\bar{p})$ channel. Unfortunately, the statistics is small and mass resolution is not so high to make a more reliable statement concerning the structures seen from the left side of the 1522 MeV peak. We also found a strong correlation of the calculated spectral lines with the enhancements on the right side from the 1522 MeV peak in the invariant mass spectrum. In this respect, it would be extremely important to improve the statistics and mass resolution of the experiment, below and above of the 1522 MeV peak, to confirm the lower and higher new exotic states predicted.

2.9 DUBNA propane bubble chamber experiment

Quite an interesting results came just recently from DUBNA experiment [15] where the 2m propane bubble chamber experimental data have been analyzed to search for the exotic baryon decaying to K_S^0-proton in the reaction p+$C_3 H_8$ at 10 GeV. The observation of three peaks in the pK_s^0 invariant mass spectrum has been reported with the masses $M_{K_S^0 p} = (1545.1 \pm 12.0, 1612.5 \pm 10.0, 1821.0 \pm 11.0)$ MeV and the measured widths of $\Gamma_{K_S^0 p} = (16.3 \pm 3.6, 16.1 \pm 4.1, 28.0 \pm 9.4)$ MeV. The statistical significance of these peaks were estimated to be of $(5.5 \pm 0,5)\sigma$, $(4.6 \pm 0.5)\sigma$ and $(6.0 \pm 0.6)\sigma$ respectively.

The effective mass distribution for 2300 pK_S^0 combination is shown in Fig. 12. The background events were analyzed using the same experimental condition. The background distribution was fitted by six-order polynomial. The solid curve in Fig. 12 represents the sum of the background and 4 Breit-Wigner resonances. As seen in Fig. 12, there are

significant enhancements in 1539, 1610 and 1810 MeV mass regions. There is also a small peak in 1980 MeV mass region.

The total (5554 combination) pK_S^0 effective mass distribution is shown in Fig. 13. The total experimental background was obtained with the same experimental condition. The significant enhancements are clear seen in Fig. 13 in 1545, 1616 and 1811 MeV mass regions. A small peak in 2.0 GeV mass region is pointed out too.

The calculated spectral lines corresponding to KK excitations in the pK^0 system taken from Table 1 have been plotted in Figs. 12 and 13 as well. Here, as in previous cases, we also found a remarkable coincidence of the calculated spectral lines with the enhancements in the invariant mass spectra.

3   Summary and Discussion

We have presented an analysis of the recent results from several experimental groups reported observation of a new Θ baryon. Our analysis was motivated by the wishes to understand a real origin of the Θ baryon and to find its place in the unified picture for hadron spectra developed early [12]. A thorough analysis of all experiments mentioned in Introduction taken together shows that, in fact, two different Θ baryons have been discovered: one $\Theta^\pm$ baryon in the $p^\pm K^0$ system and other Θ^+ baryon in the nK^+ system. It's our first claim.

We have established that both Θ baryons are excellently incorporated in the unified picture for hadron spectra: the $\Theta(pK_S^0)$ baryon lives on the six storey in Kaluza-Klein tower for pK^0 system but the $\Theta(nK^+)$ baryon lives on the seven storey in Kaluza-Klein tower for nK^+ system; see Table 1.

As is seen from Table 1, almost all experimentally filled storeys in Kaluza-Klein tower for kaon-nucleon system contain pairs of Σ and Λ particles with negative strangeness. One might think that $\Theta(pK_S^0)$ baryon represents an isovector with positive strangeness partner of isoscalar $\Lambda(1520)$ particle with negative strangeness, and $\Theta(nK^+$ baryon is isoscalar with positive strangeness partner of isovector $\Sigma(1560)$ particle with negative strangeness. In this respect, it would be quite an important to set up purposeful experiments to search for the states $\Sigma(1520) \in M_6^{NK}(1524-1528) \bigcup M_8^{\Lambda\pi}(1522-1524)$ and $\Lambda(1560) \in M_7^{NK}(1555-1560)$. It would also be very interesting an attempt to seek a rare decay mode $\Lambda(1520) \to \Lambda\pi$ with an isospin violation (see 8-storey in Table 2). From strong correlation between spectral lines corresponding to Kaluza-Klein tower for kaon-nucleon system and the peaks on the histograms established above, one can conclude that there exist positive srangeness Θ partners for all Σ and Λ particles with negative strangeness as we predicted – this is our second claim. The most impressive manifestation and confirmation of that claim we found in neutrino interactions data set [5]. Our predictions should be tested in the future experimental studies.

The properties of the observed Θ states, such as spin, isospin, and parity are not established in the above mentioned experiments. So, it is important to measure the quantum numbers of the Θ particles in the future experiments. In our opinion, a classification of baryons by soliton configurations in chiral field theories is more preferable compared to the standard quark model classification. In particular, the SU(3) version of the chiral soliton model [10] predicts the Θ^+ state of having spin 1/2, isospin 0, and positive parity. Attractive in the soliton classification scheme that the Θ baryon is considered on an

equal ground with other baryons. This is ideologically close to our scheme of systematics. However, our description significantly differs in many important things from the chiral soliton description.

Our conservative estimate for the widths of KK excitations looks like $\Gamma_n \sim 0.4 \cdot n$ Mev, where n is the number of KK excitation. This gives $\Gamma_6(\Theta^\pm) \sim 2.4$ Mev and $\Gamma_7(\Theta^+) \sim 2.8$ Mev. Thus, a more careful experimental studies with a higher statistics and mass resolution are extremely important.

Here, we should like to bring up some comments on the problems under discussion. If one takes the structures below and above of the Θ peak in the $K_S^0 p$ invariant mass spectra observed in [13, 14, 15] seriously, then we come to the conclusion that the experimentally observed picture is not at all what is predicted by the chiral soliton model. As an additional argument in favor of that claim we would like to refer to the recent, interesting article [16] where a careful analysis of K^+d total cross section data was undertaken to explore possible manifestations of the resonance in the S=+1 hadronic system with mass around 1.55 GeV. It was found that a structure corresponding to the resonance is visible in the data. The width consistent with the observed deviation from background was found to be 0.9±0.2 MeV and the mass is 1.559±0.003 GeV for the spin parity $\frac{1}{2}^+$ and 1.547±0.002 GeV for $\frac{1}{2}^-$. Perhaps this is the first experimental verdict on a crucial problem concerning the quantum numbers of the Θ baryon. The obtained mass 1.559±0.003 GeV for the spin parity $\frac{1}{2}^+$ is in excellent agreement with the $M_7^{nK^\pm}(1556\,\text{MeV})$-storey in Kaluza-Klein tower for kaon-nucleon system (see Table 1) and far enough from accurate prediction 1530 MeV in [10]. The mass 1.547±0.002 GeV is closer to the prediction 1530 MeV but the negative parity ($\frac{1}{2}^-$) in that case contradicts to the predicted [10] positive parity ($\frac{1}{2}^+$). We would also like to point out, once again, a noticeable spread among the masses of the Θ states observed in different experiments. However, it should be noted that the CLAS Collaboration [6] reported a very small statistical error on the mass of the Θ^+ which is 1555±1(stat.) MeV. The large error in the quoted mass [6] was due to possible systematic errors. The mass value 1555±1(stat.) MeV is in excellent agreement with the $M_7^{nK^\pm}(1556\,\text{MeV})$-storey in the Kaluza-Klein tower for kaon-nucleon system as well, and this might be considered as an additional argument in favor of the spin parity $\frac{1}{2}^+$. Certainly, this is a remarkable fact that it may be possible to infer the parity of the state from a comparison of its mass values [16]. In this respect a more accurate experimental measurement and precise determination of the masses of the Θ states is a question of vital importance as well. No doubt, further measurements to obtain a more accurate kaon-nucleon scattering data would be very useful to better establish all possible states in kaon-nucleon system with positive and negative strangeness simultaneously.

We have already claimed that the year 2003 will enter the history of particle physics as a year of fundamental discoveries [12]. This concerned a series of new narrow mesons states discovered at the masses which are surprisingly far from the predictions of conventional quark potential models. Exciting experimental measurements in baryons spectroscopy in the same year and next with discovery of the Θ baryon states provided an additional excellent confirmation of that claim. All of these discoveries in meson and baryon spectroscopy clearly open a new page in hadron physics which is certainly a starting page of a new era in particle physics. One might think that this is an era of the extra dimensions.

Acknowledgements

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Table 1: Kaluza-Klein tower of KK excitations for kaon-nucleon system and experimental data. The Θ^+ mass values have been taken from Refs. [6, 7].

n	$M_n^{nK^\pm}$ MeV	$M_n^{pK^0}$ MeV	$M_n^{nK^0}$ MeV	$M_n^{pK^\pm}$ MeV	M_{exp}^{NK} MeV
1	1435.90	1438.59	1439.88	1434.61	
2	1443.82	1446.47	1447.76	1442.53	
3	1456.89	1459.48	1460.77	1455.61	
4	1474.92	1477.43	1478.71	1473.65	$\Sigma(1480)$
5	1497.66	1500.08	1501.35	1496.40	
6	1524.84	1527.16	1528.41	1523.59	$\Lambda(1520)$ $\Theta^+(pK_S^0)(1527\pm2.3)$
7	1556.15	1558.36	1559.60	1554.92	$\Sigma(1560)$ $\Theta^+(nK^+)(1555\pm10)$
8	1591.30	1593.39	1594.61	1590.07	$\Sigma(1580)$ $\Lambda(1600)$
9	1629.96	1631.95	1633.16	1628.76	$\Sigma(1620)$ $\Lambda(1600)$
10	1671.87	1673.76	1674.94	1670.69	$\Sigma(1670)$ $\Lambda(1670)$
11	1716.75	1718.53	1719.69	1715.59	$\Sigma(1690)$ $\Lambda(1690)$
12	1764.35	1766.02	1767.17	1763.20	$\Sigma(1770)$ $\Lambda(1800)$
13	1814.42	1816.01	1817.13	1813.30	$\Sigma(1840)$ $\Lambda(1830)$
14	1866.77	1868.26	1869.36	1865.67	$\Sigma(1880)$ $\Lambda(1890)$
15	1921.19	1922.60	1923.68	1920.11	$\Sigma(1915)$
16	1977.51	1978.85	1979.90	1976.46	$\Sigma(1940)$ $\Lambda(2000)$
17	2035.57	2036.84	2037.87	2034.54	$\Sigma(2030)$ $\Lambda(2020)$
18	2095.23	2096.43	2097.44	2094.22	$\Sigma(2080)$ $\Lambda(2100)$
19	2156.35	2157.49	2158.48	2155.36	$\Sigma(2100)$ $\Lambda(2110)$
20	2218.82	2219.90	2220.87	2217.85	$\Sigma(2250)$
21	2282.52	2283.55	2284.50	2281.57	
22	2347.37	2348.35	2349.28	2346.44	$\Lambda(2350)$
23	2413.27	2414.20	2415.11	2412.36	
24	2480.14	2481.03	2481.92	2479.25	
25	2547.91	2548.76	2549.63	2547.04	$\Lambda(2585)$
26	2616.50	2617.32	2618.17	2615.66	$\Sigma(2620)$
27	2685.88	2686.66	2687.49	2685.04	
28	2755.96	2756.72	2757.53	2755.15	
29	2826.71	2827.44	2828.23	2825.92	
30	2898.08	2898.78	2899.56	2897.30	

Table 1: Kaluza-Klein tower of KK excitations for $\Lambda\pi$ system and experimental data.

n	$M_n^{\Lambda\pi^0}$MeV	$M_n^{\Lambda\pi^\pm}$MeV	$M_{exp}^{\Lambda\pi}$MeV
1	1257.66	1262.06	
2	1277.20	1281.13	
3	1306.19	1309.59	
4	1341.85	1344.77	
5	1382.26	1384.79	$\Sigma(1385)$
6	1426.24	1428.46	
7	1473.06	1475.02	$\Sigma(1480)$
8	1522.24	1524.00	$\Sigma(\Lambda)(1520)$??
9	1573.47	1575.06	$\Sigma(1560)$
10	1626.52	1627.96	$\Sigma(1620)$
11	1681.22	1682.55	$\Sigma(1670)$
12	1737.44	1738.66	$\Sigma(1750)$
13	1795.06	1796.20	$\Sigma(1840)$
14	1853.99	1855.05	$\Sigma(1880)$
15	1914.15	1915.14	$\Sigma(1915)$
16	1975.46	1976.39	$\Sigma(1940)$
17	2037.84	2038.72	$\Sigma(2030)$
18	2101.24	2102.07	$\Sigma(2080)$
19	2165.60	2166.39	$\Sigma(2100)$
20	2230.87	2231.62	$\Sigma(2250)$
21	2296.98	2297.69	
22	2363.89	2364.57	
23	2431.56	2432.21	
24	2499.94	2500.57	
25	2568.99	2569.59	
26	2638.68	2639.26	
27	2708.96	2709.52	
28	2779.81	2780.35	
29	2851.19	2851.71	
30	2923.07	2923.58	
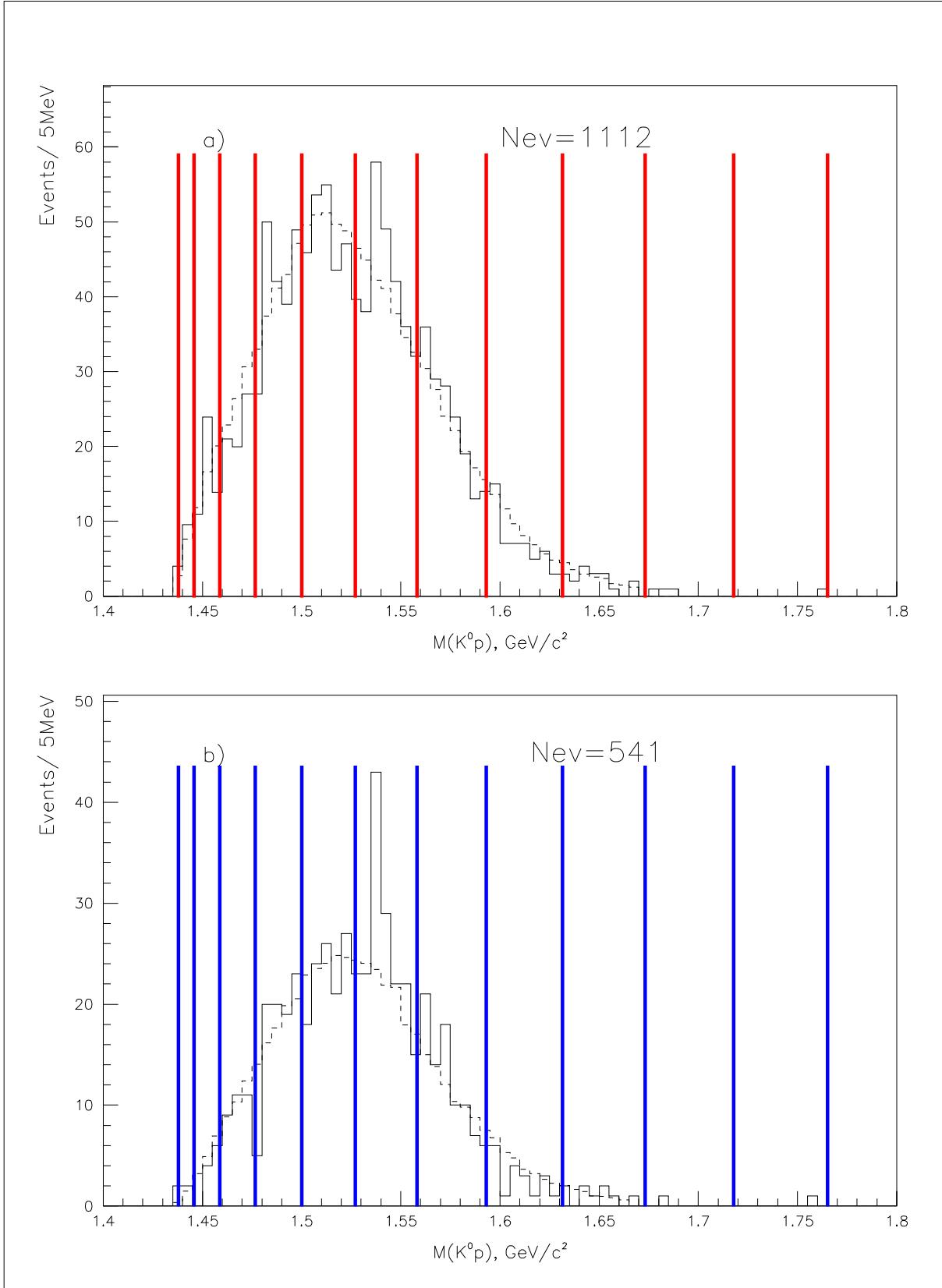
Figure 1: Effective mass of the K^0p system formed in the reaction $K^+\mathrm{Xe} \rightarrow K^0p\mathrm{Xe}'$ extracted from Ref. [2]: (a) for all measured events, (b) for events that pass additional selections; see [2]. The vertical (spectral) lines correspond to KK tower for K^0p system; see Table 1.

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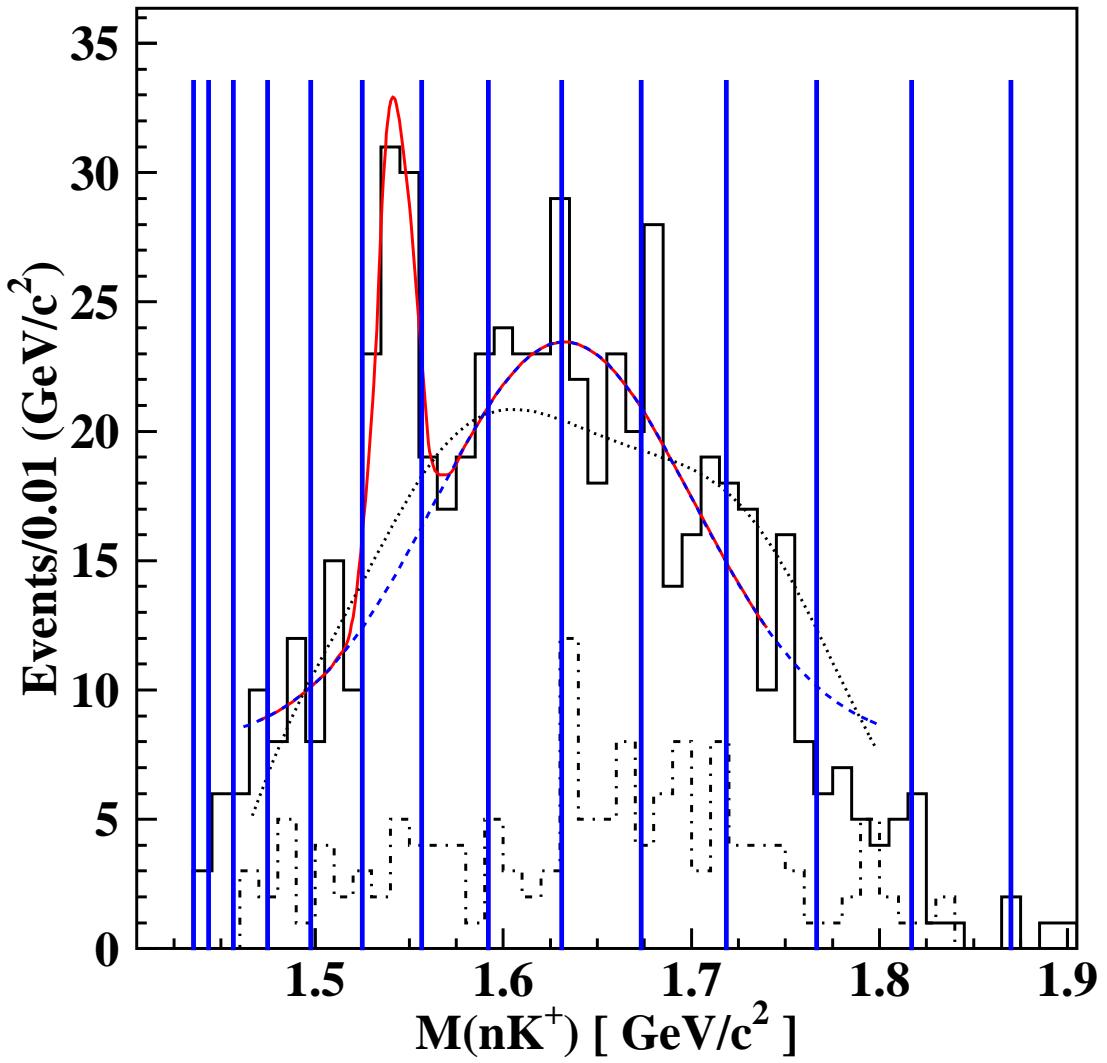
Figure 2: Invariant mass of the nK^+ system extracted from Ref. [3]. The vertical (spectral) lines correspond to KK tower for nK^+ system; see Table 1.
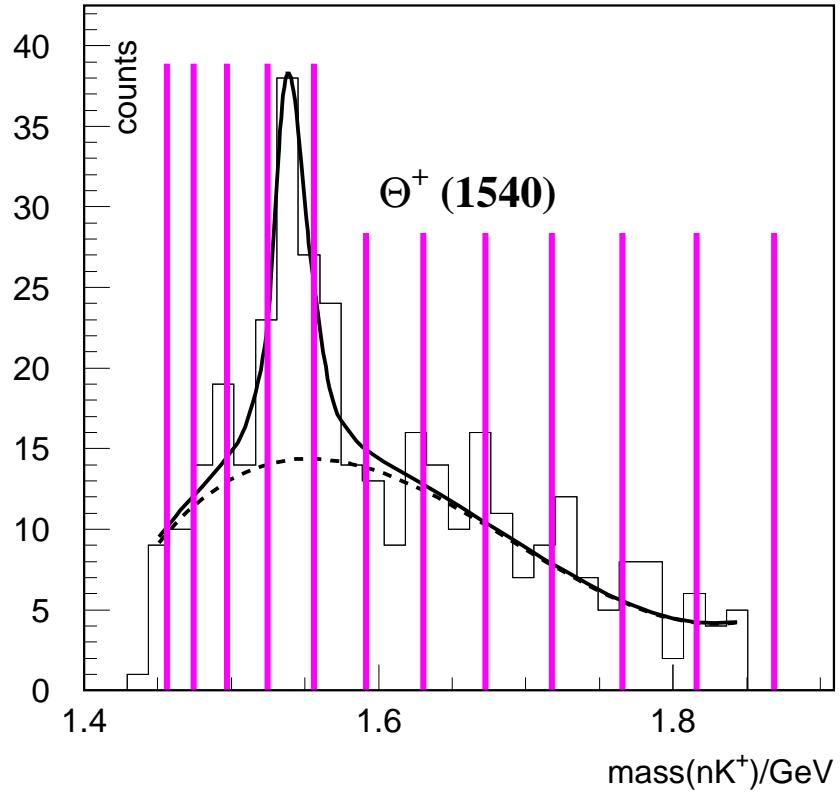
Figure 3: The nK^+ mass distribution after cuts in the $\pi^+\pi^-$ mass distribution and in the K_S^0 production angle extracted from Ref. [4]. The solid line represents a fit using a Breit–Wigner distribution (convoluted with a resolution function) plus polynomial background; see [4] for details. The vertical (spectral) lines correspond to KK tower for nK^+ system; see Table 1.
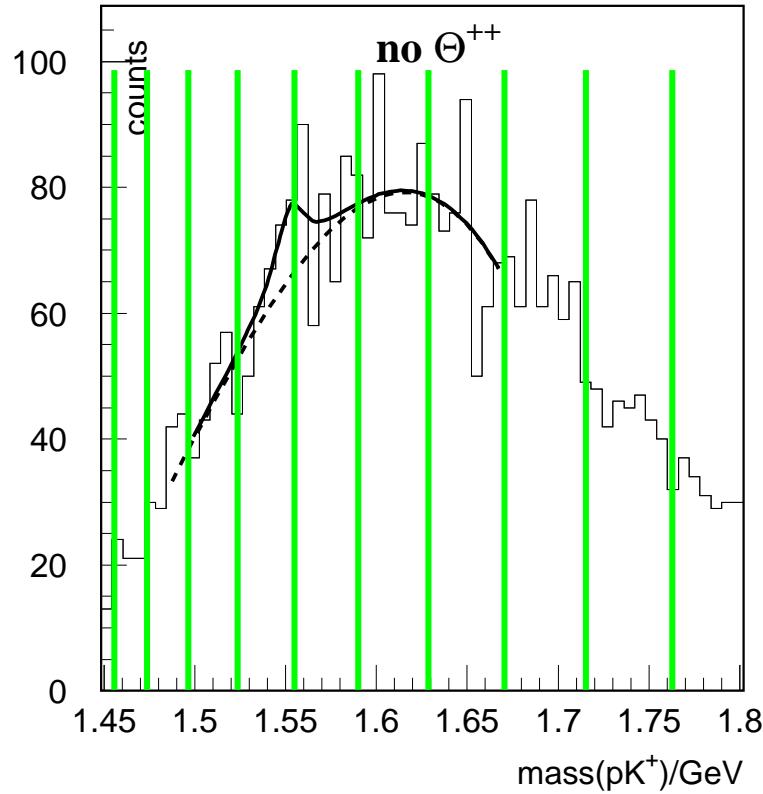
Figure 4: The pK^+ invariant mass distribution in the pK^+K^- final state extracted from Ref. [4]. The solid line represents a fit using a Breit–Wigner distribution (convoluted with a resolution function) plus polynomial background; see [4] for details. The vertical (spectral) lines correspond to KK tower for pK^+ system; see Table 1.
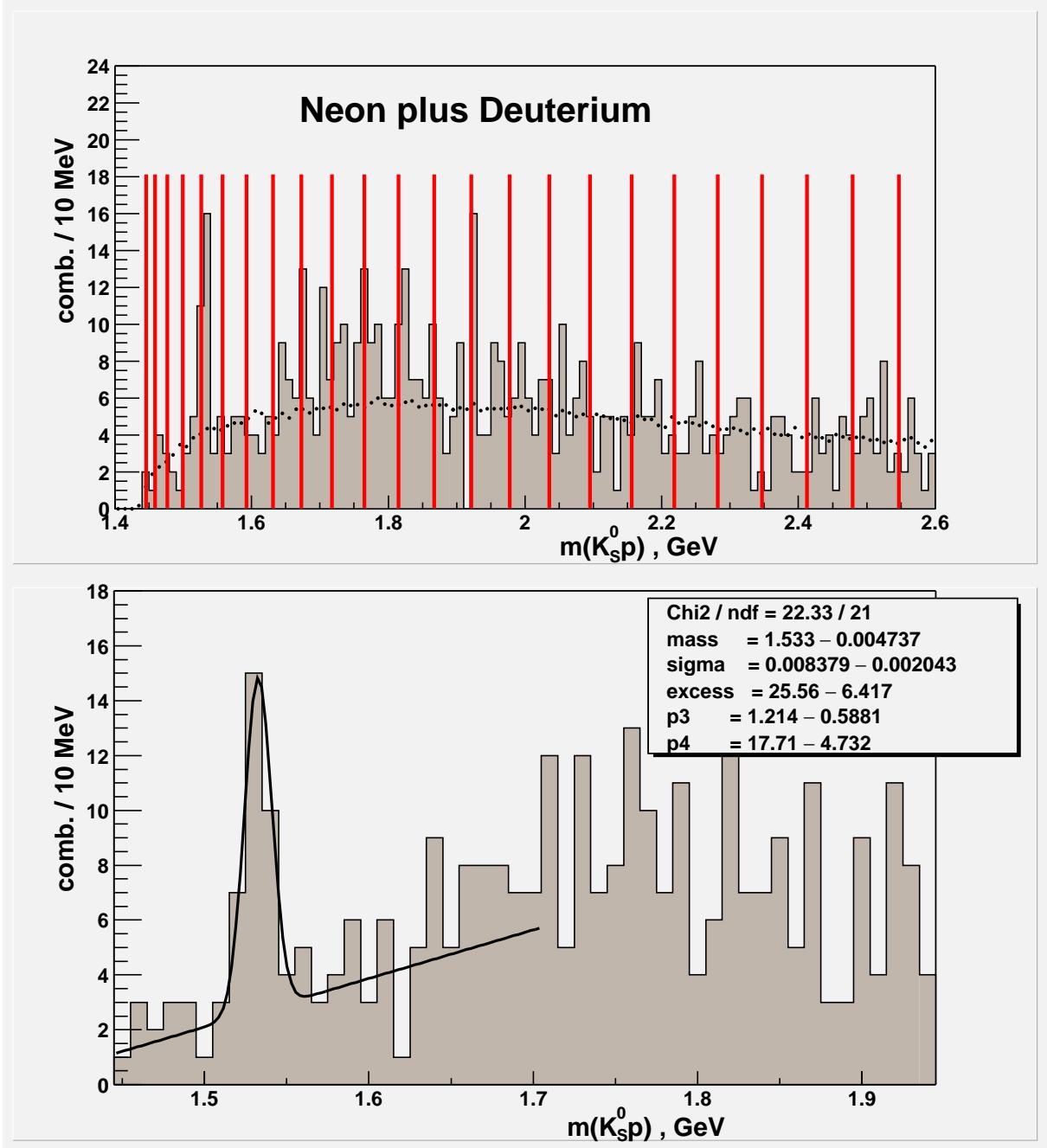
Figure 5: Extracted from Ref. [5] the $K_S^0 p$ invariant mass distribution for the Neon and Deuterium data combined (top panel). The dots depict the random-star background. The vertical (spectral) lines correspond to KK tower for pK^0 system; see Table 1. A fit of the same $K_S^0 p$ distribution but plotted with shifted bins is shown in the bottom panel; see [5] for details.
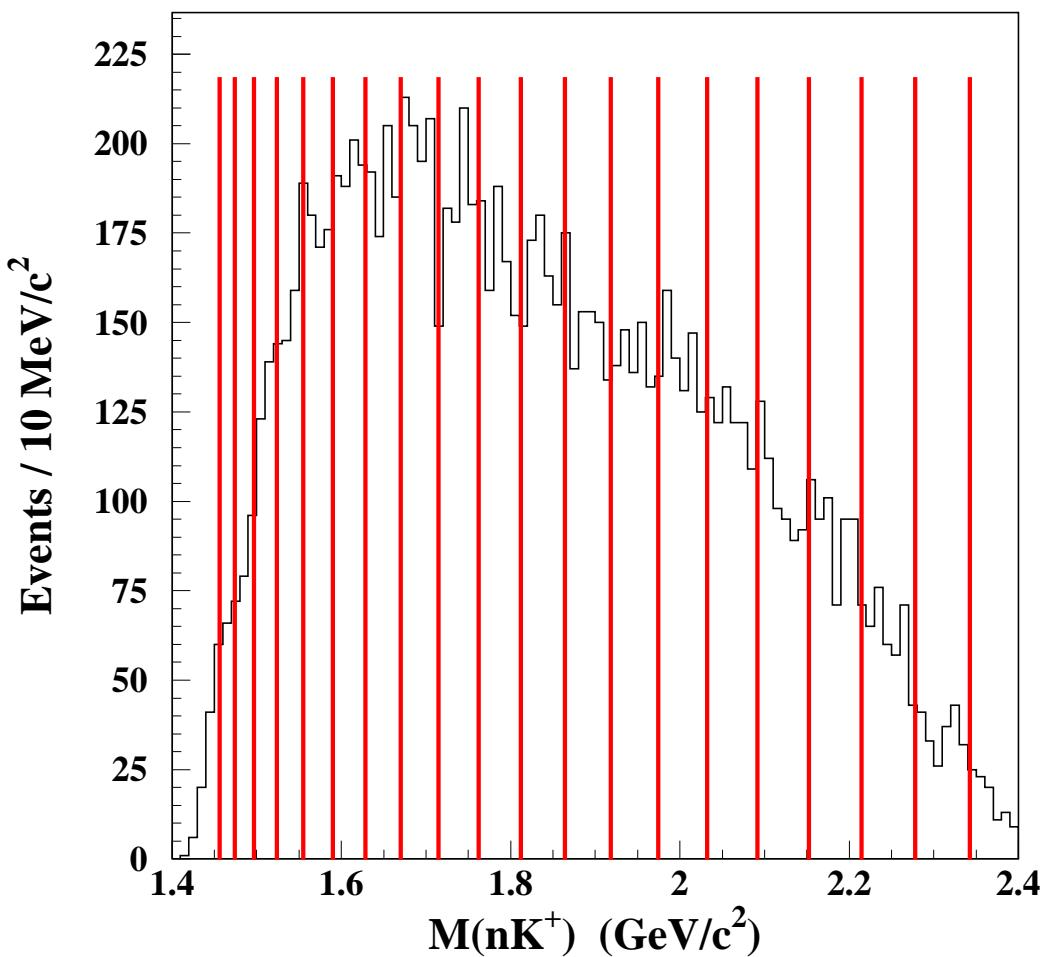
Figure 6: The nK^+ invariant mass spectrum in the reaction $\gamma p \to \pi^+ K^- K^+(n)$ extracted from Ref. [6]. The vertical (spectral) lines correspond to KK tower for nK^+ system; see Table 1.
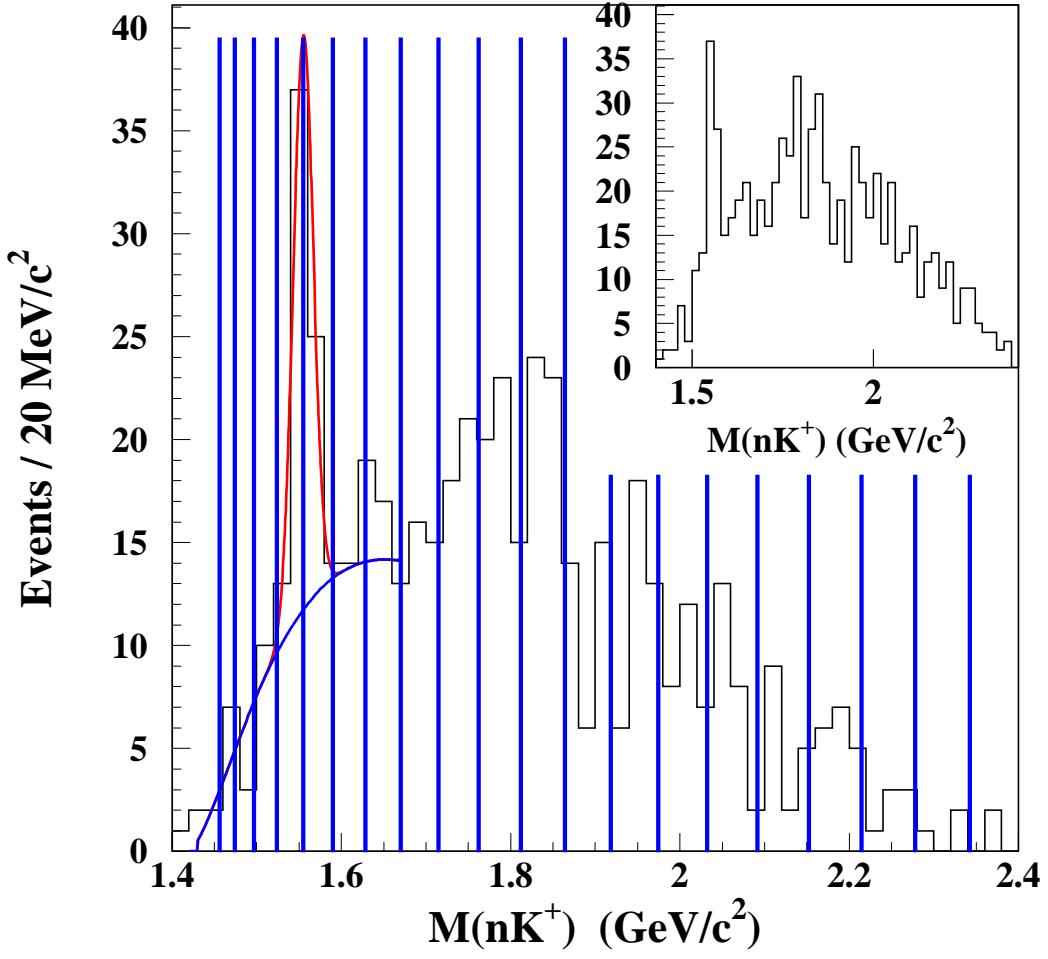
Figure 7: Extracted from Ref. [6] the nK^+ invariant mass spectrum in the reaction $\gamma p \to \pi^+ K^- K^+ (n)$ with the cut $\cos\theta^*_{\pi^+} > 0.8$ and $\cos\theta^*_{K^+} < 0.6$. $\theta^*_{\pi^+}$ and $\theta^*_{K^+}$ are the angles between the π^+ and K^+ mesons and photon beam in the center-of-mass system. The vertical (spectral) lines correspond to KK tower for nK^+ system; see Table 1. The inset shows the nK^+ invariant mass spectrum with only the $\cos\theta^*_{\pi^+} > 0.8$ cut; see [6] for details.
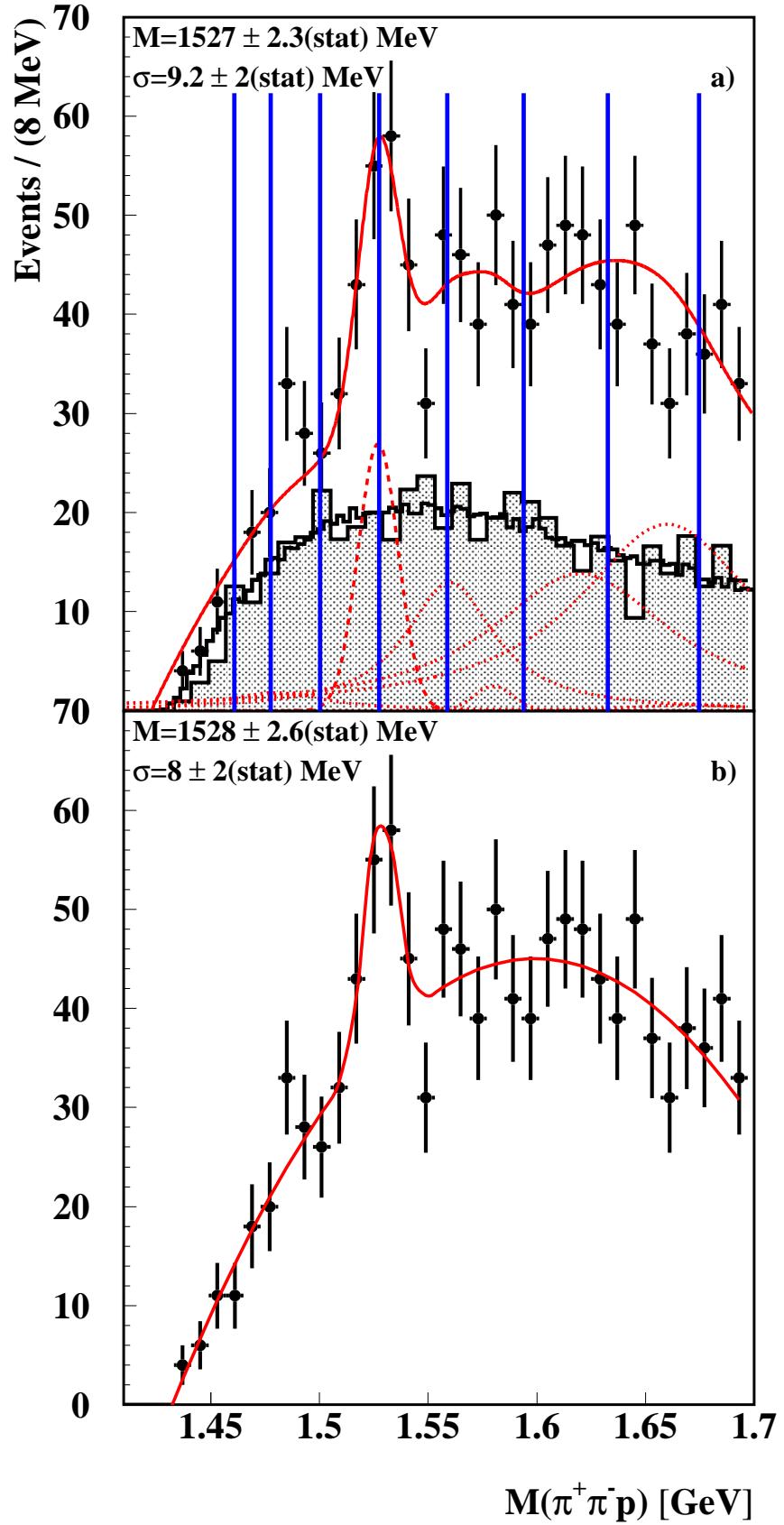
Figure 8: Distribution in invariant mass of the $p\pi^+\pi^-$ system subject to various constraints described in Ref. [7]. In top panel the Phythia6 Monte Carlo simulation is represented by the gray shaded histogram; see [7] for details. The vertical (spectral) lines in top panel correspond to KK tower for $K^0 p$ system; see Table 1.
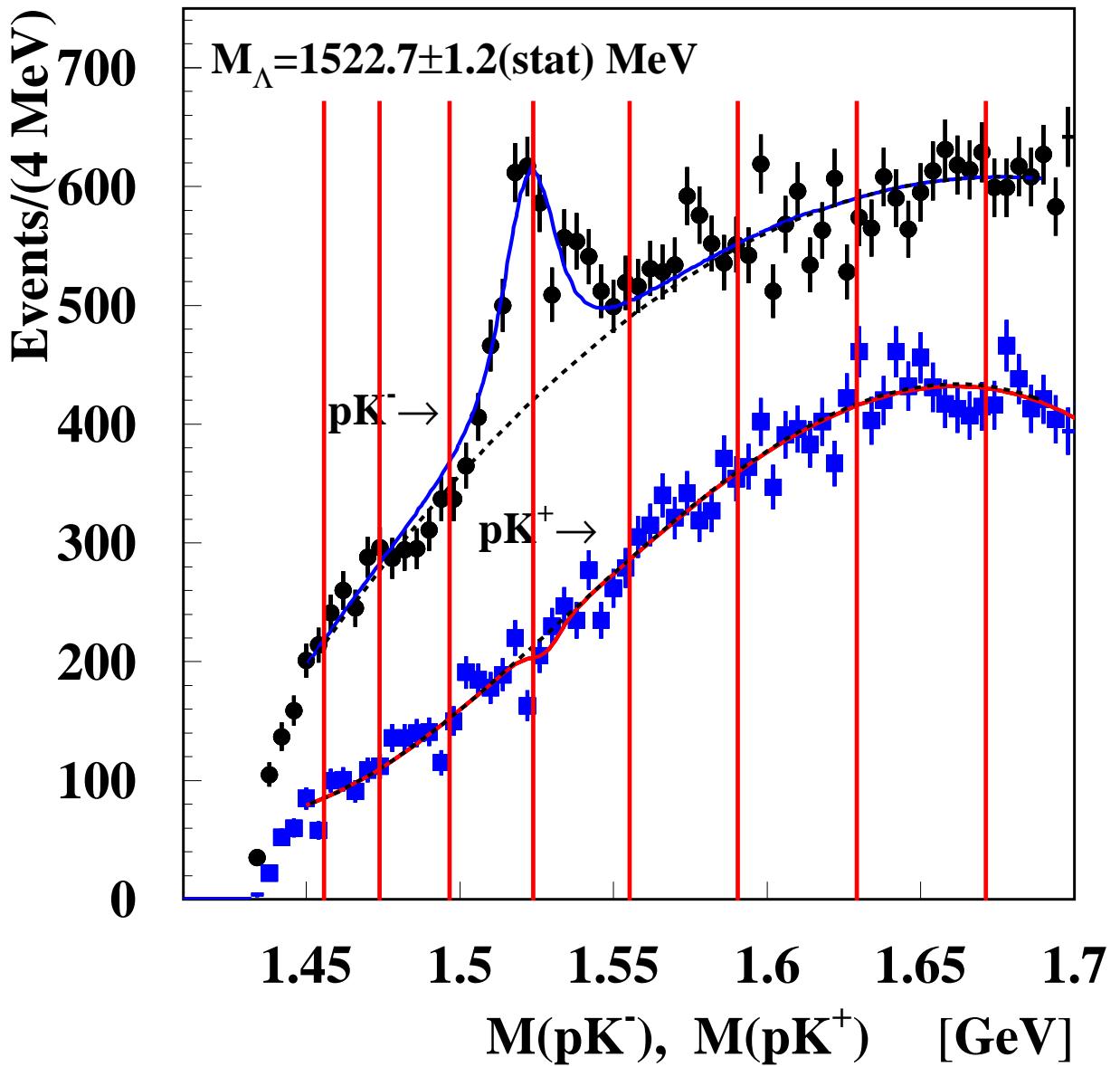
Figure 9: Spectra of invariant mass M_{pK^-} (top) and M_{pK^+} (bottom) extracted from Ref. [7]. The vertical (spectral) lines correspond to KK tower for $K^{\pm}p$ system; see Table 1.
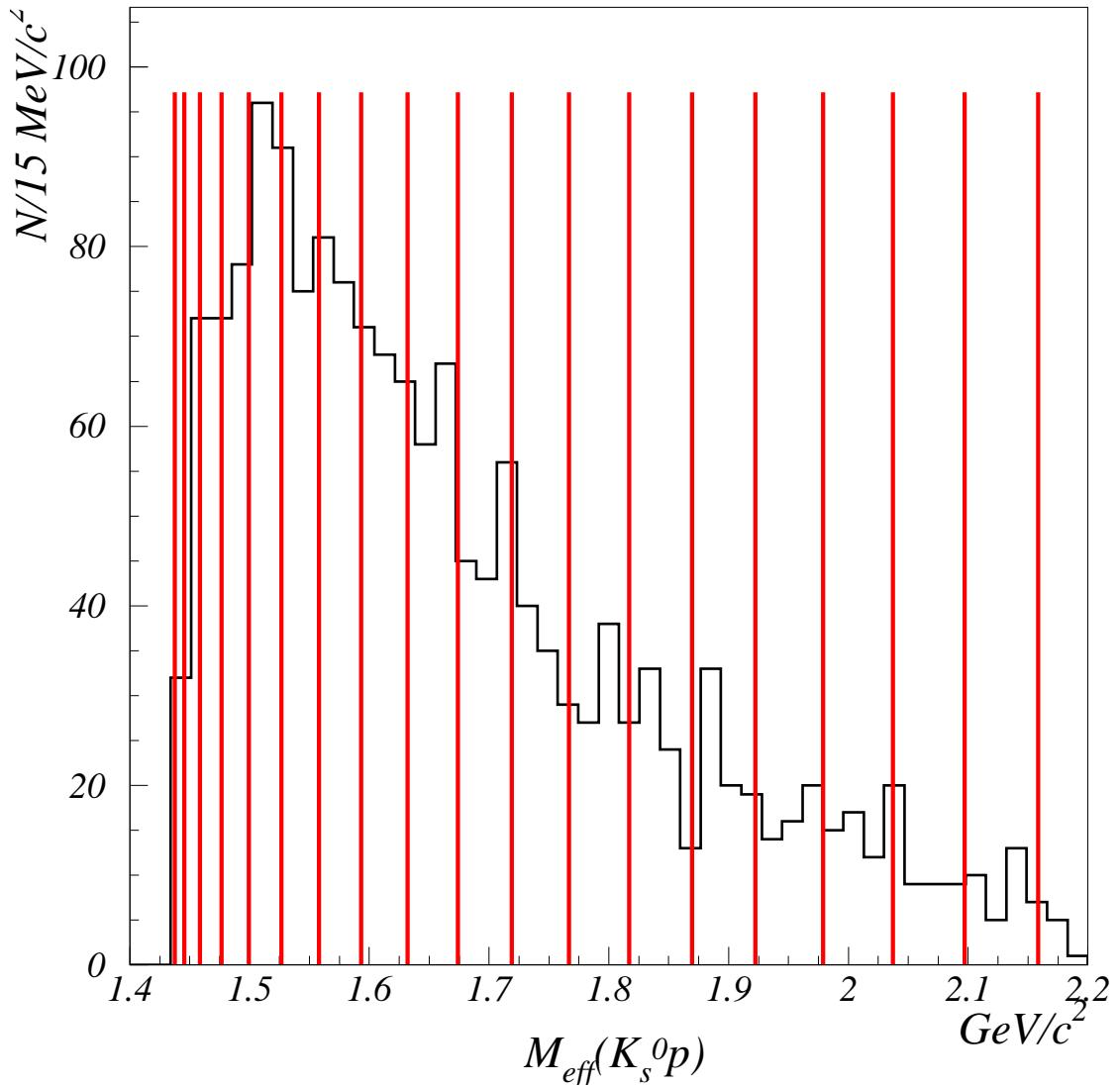
Figure 10: The (pK_S^0) invariant mass spectrum in the reaction $pA \rightarrow pK_S^0A + X$ before the cuts extracted from Ref. [9]. The vertical (spectral) lines correspond to KK tower for K^0p system; see Table 1.

ZEUS

$K^0_S p(\bar{p})$

$Q^2 > 20$ GeV^2

χ^2 / ndf = 35 / 44

peak = 1521.5 − 1.5 MeV

width = 6.1 − 1.6 MeV

events = 221 − 48

- ZEUS 96-00
- Fit
- Gaussian
- Background
- ARIADNE MC

$K^0_S p$
$K^0_S \bar{p}$
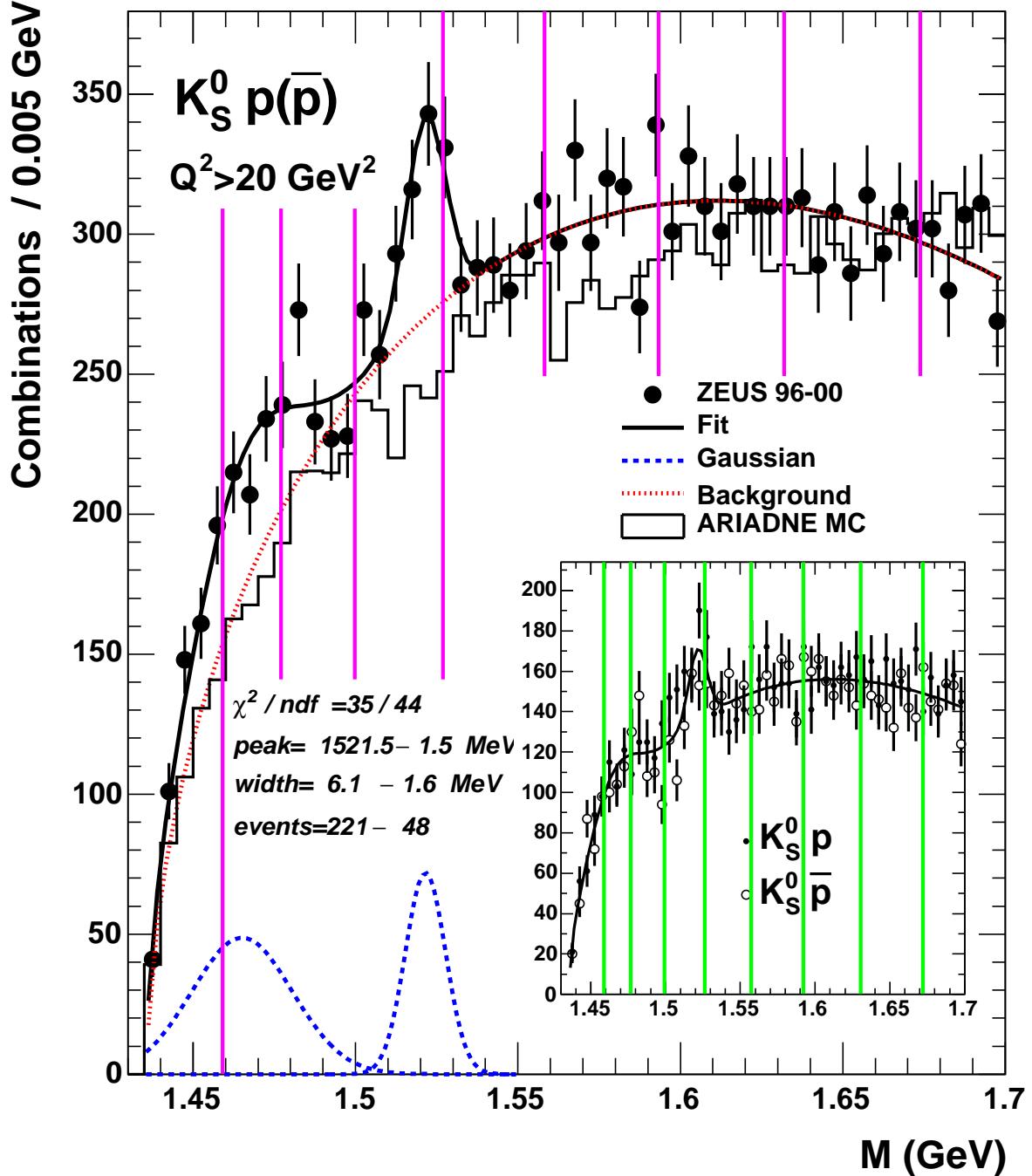
Figure 11: Invariant-mass spectrum for the $K^0_S p(\bar{p})$ channel for $Q^2 > 20$ GeV^2 extracted from Ref. [13]. The solid line is the result of a fit to the data using a three-parameter background function plus two Gaussians (see [13]). The dashed lines show the Gaussian components and the dotted line the background according to this fit. The histogram shows the prediction of the ARIADNE MC simulation normalized to the data in the mass region above 1650 MeV. The inset shows the $K^0_S \bar{p}$ (open circles) and the $K^0_S p$ (black dots) candidates separately, compared to the result of the fit to the combined sample scaled by a factor of 0.5. The vertical (spectral) lines correspond to KK tower for $K^0 p$ system; see Table 1.

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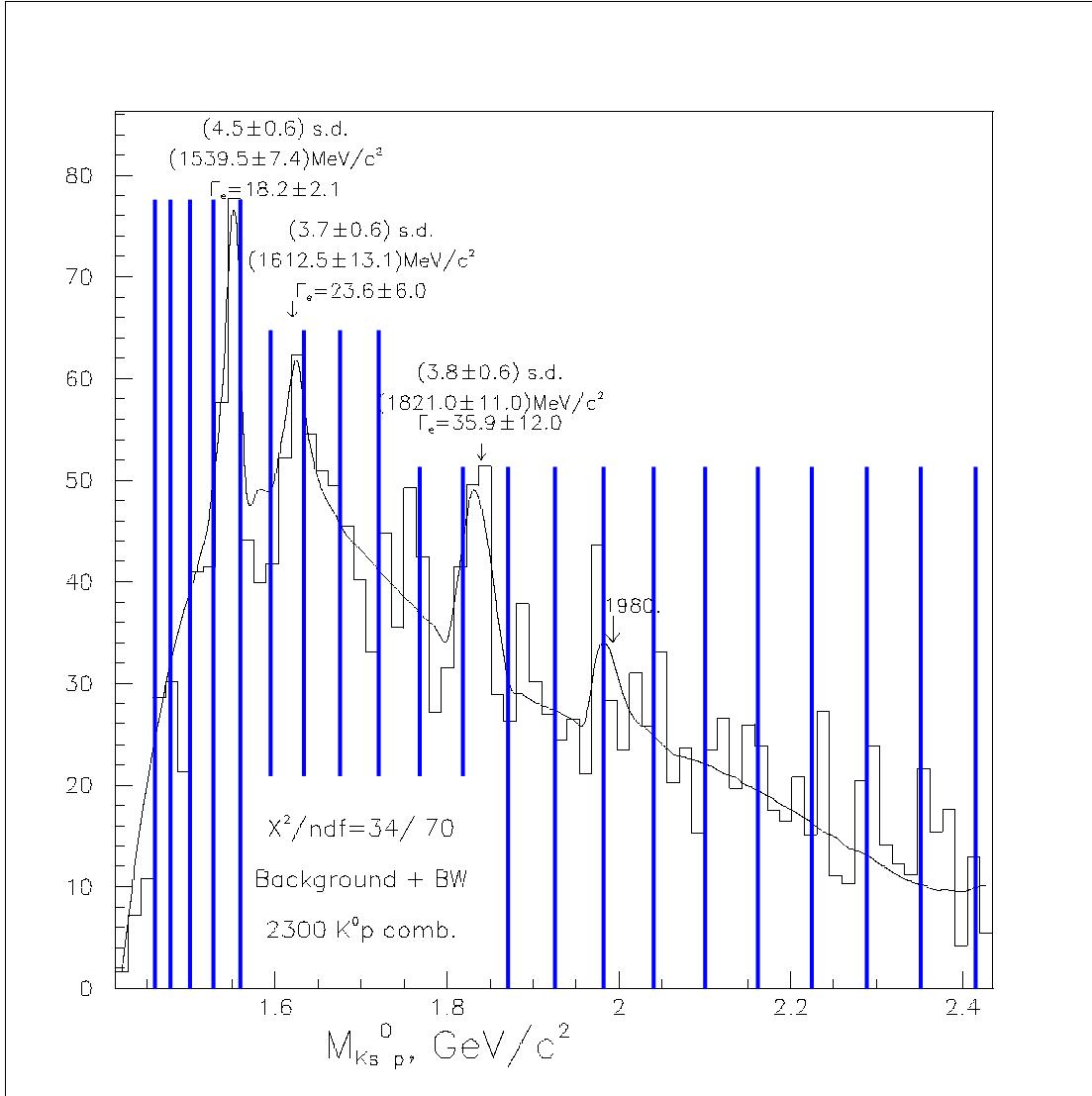
Figure 12: The pK_S^0 invariant-mass spectrum with the momentum of $0.350 \leq p \leq 0.900\text{GeV/c}$ for identified protons in the reaction p+$C_3H_8 \rightarrow pK_s^0$ + X extracted from Ref. [15]. The solid curve represents the sum of the experimental background and 4 Breit-Wigner resonances. The experimental background was approximated by six-order polynomial. The vertical (spectral) lines correspond to KK tower for K^0p system; see Table 1.
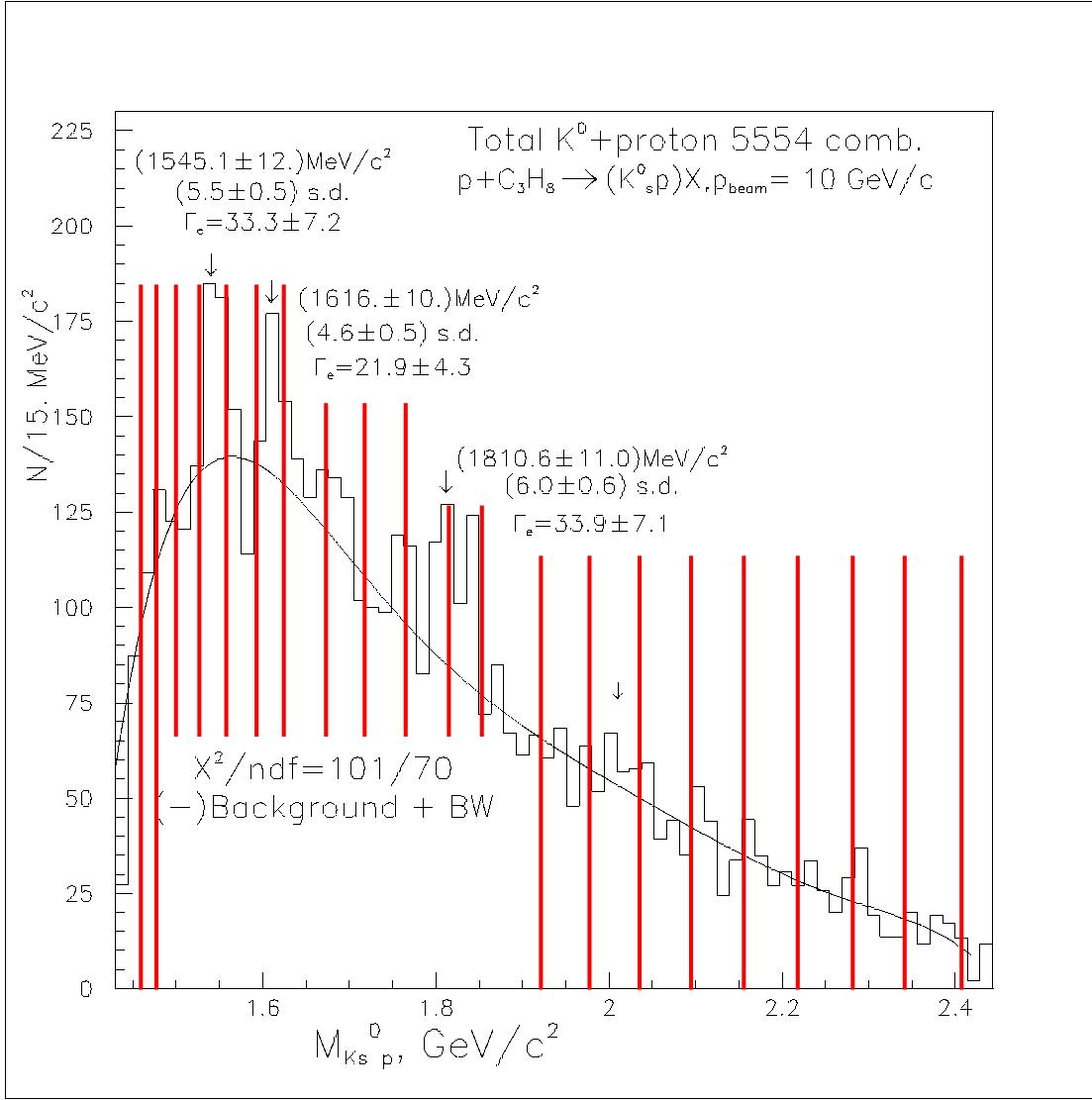
Figure 13: The $K^0_S p$ effective mass distribution combined for protons with the momenta $0.350 \leq p \leq 0.9$ GeV/c^2 and $p \geq 1.7 GeV/c^2$ extracted from Ref. [15]. The curve is the experimental background taken in the form of six-order polynomial. The vertical (spectral) lines correspond to KK tower for $K^0 p$ system; see Table 1.